SLA–Mechanisms for Electricity Trading under Volatile Supply and Varying Criticality of Demand

(Extended Abstract)

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ABSTRACT

The increasing adoption of renewable power generation makes volatile quantities of electricity available, the delivery of which cannot be guaranteed, if sold. However, if not sold, the electricity might need to be curtailed, thus foregoing potential profits. In this paper we adapt service level agreements (SLAs) for the future smart electricity grid, where generation will primarily depend on volatile and distributed renewable power sources, and where buyers' ability to cope with uncertainty may vary significantly. We propose a contracting framework through SLAs to allocate uncertain power generation to buyers of varying preferences. These SLAs comprise quantity, reliability and price. We define a characterization of the value degradation of tolerant and critical buyers with regards to the uncertainty of electricity delivery (generalizing the Value of Lost Load, VoLL). We consider two mechanisms (sequential second-price auction and VCG) that allocate SLAs based on buyer bids. We further study the incentive compatibility of the proposed mechanisms, and show that both mechanisms ensure that no buyer has an incentive to misreport its valuation. We experimentally compare their performance and demonstrate that VCG dominates alternative allocations, while vastly improves the efficiency of the proposed system when compared to a baseline allocation considering only the VoLL. This article lays the ground work for distributed energy trading under uncertainty, thereby contributing an essential component to the future smart grid.

1. INTRODUCTION

One of the biggest challenges that future energy systems will face due to the increasing adoption of renewable power generation is to maintain balance between available supply and demand. To this end demand-side management (DSM) is necessary. DSM is the behavior change of the demand-side, which can be enabled through, e.g., financial incentives [4]. Dynamic pricing and scheduling of consumption loads are considered as the main methodologies for balancing demand with uncertain supply. However, the former may introduce disruptive and unfavorable market behavior and thus planning and ahead prices are required [2], while the latter can violate the autonomy of the consumer agents. Other variants of DSM focus on the design of tariffs that forward the financial risks of balancing supply and demand to the demand-side [11, 15, 12].

Service level agreements (SLAs) can provide the contracting framework for balancing volatile supply with demand between buyers and sellers of electricity. While previous work has considered SLAs as a tool for monitoring and coordination to ensure trustworthiness between different stakeholders [5], or as a negotiation protocol [1], we interpret SLAs as a direct extension of conventional electricity tariffs.

To the best of our knowledge, we propose the first approach that adapts SLAs for energy trading under uncertain supply. We also provide two mechanisms to allocate SLAs to buyers of different preferences with regards to the criticality of their demand. The main contributions of this work can be summarized as follows:

- We define a contracting framework through SLAs that enables energy trading under uncertain supply.
- We propose an exponential family of functions that characterizes the buyers' varying degrees of criticality, thus generalizing the Value of Lost Load with costs associated to the risk of failed delivery.
- We apply two mechanisms to assign SLAs to agents of different types, and incentivize truthfulness for strategic buyer agents.
- Results show that the social value vastly improves in face of buyers with varying abilities to cope with uncertainty.

2. CONTRIBUTION

In the proposed framework we assume that there is a single seller (producer) with uncertain generation. Ahead of time, the generation can be represented by the random variable Q, while in the realization step, $q \in \mathbb{R}^+$ denotes the observed supply. Figure 1 (left) illustrates the function $S(q)$, which denotes the reliability function of the generation. The reliability function determines the probability that the generation exceeds a certain value of q, and therefore can satisfy any demand up to the observed generation q.

We further consider the set $\mathcal{B}$ of buyers, each of which has a demand d_i that needs to be satisfied. However, given the reliability function, not all demand may be served with probability equal to 1. Therefore, we introduce SLAs that comprise the following features:

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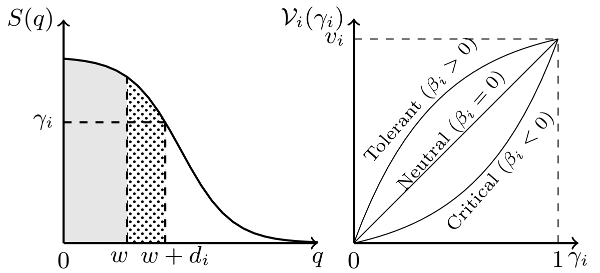

Figure 1: (Left) Reliability function $S(q) = P(Q > q)$ of the random variable Q. The dotted area represents the portion of demand d_i of the buyer agent i with reliability $\gamma_i = S(w + d_i)$. The gray shaded area represents already assigned SLAs. (Right) The expected value $\mathcal{V}_i$ of a buyer agent with regards to the reliability γ_i of an SLA.

Quantity The quantity of electricity that is subject to be transferred from the service provider to the user.

Reliability The probability of successful delivery of the given quantity of electricity.

Price The price per unit of the transferred quantity.

Considering Figure 1 (left), the dotted area represents an SLA between the seller and the buyer agents. The demand of the buyer i is d_i and the reliability of the specific SLA is $\gamma_i = S(w + d_i)$, where w is the demand that is already deducted by previously allocated SLAs.

The widest adopted concept to measure criticality in the literature as well as in practice is the *Value of Lost Load* (VoLL)[8]. The VoLL is defined as the estimated amount that customers receiving electricity through contracts would be willing to pay to avoid a disruption in their electricity service. However, no previous work establishes a metric for the valuation of electricity with regards to the uncertainty in the delivery. Since the system gives raise to risk, we first distinguish between different attitudes of energy buyers towards the certainty of delivery, as is usual in economics and expected utility theory [7]. More specifically, we categorize buyer agents with respect to their attitudes towards reliability as follows: *critical* (the expected value function is convex, representing a risk-averse buyer), *tolerant* (the expected value function is concave, the buyer is risk-seeking), and *neutral* (the expected value is linearly dependent to the reliability). Figure 1 (right) illustrates the value function $\mathcal{V}_i(\gamma_i)$, the value of β_i distinguishes different attitudes of buyer i towards the reliability γ_i. The proposed value function generalizes the concept of the VoLL with regards to the risk of unsuccessful delivery.

The process of specifying and allocating SLAs to buyers participating in the electricity market can be structured as a mechanism [6]. We consider auctions as the mechanism to allocate SLAs among buyers with varying private preferences, since they are widely used in competitive electricity markets [3]. More specifically, we apply two auction mechanisms to allocate supply that may become available at the realization timestep: a sequential second-price auction (SSPA) [10, 14], and the Vickrey-Clarke-Groves (VCG) [13]. In SSPA, SLAs are auctioned off one at a time, while in VCG SLAs are allocated in a socially optimal manner, thus maximizing the social value. Assuming unit-demand buyers, it can be shown that computing the optimal allocation in the VCG mechanism can be solved optimally in polynomial time $\mathcal{O}(n^3)$ by the *Hungarian method*, given that it is equivalent to the *linear assignment problem* [9]. Under some realistic, for the setting, assumptions (e.g., no price discovery, no overbidding) both mechanisms are dominant strategy incentive compatible (DSIC). The dominant strategy of buyers is to truthfully report their valuations.

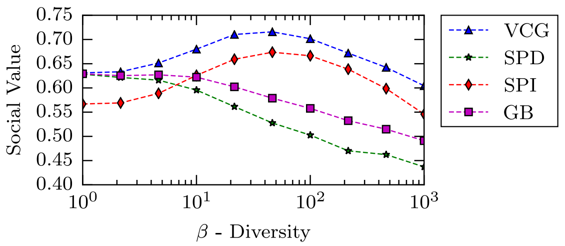

Figure 2: Social value with regards to the diversity of criticality, for very low values of β-diversity all buyers have neutral attitude towards uncertainty in the delivery. For higher values of β-diversity buyers have increasingly varying criticality.

Figure 2 presents the social value (average value gained per buyer resulting from the assignement of the SLAs over 100 simulations) for varying diversity of the criticality β, where β is sampled uniformly in the range $[-D, D]$ (D is the β-diversity). The random variable of the supply, Q, is normally distributed ($\mu_Q = 20, \sigma_Q = 5$), while the total demand exceeds the expected supply by 20% (24 unit-demand buyers). We illustrate the social value under four different mechanisms: VCG, SSPA with decreasing/increasing reliability SLAs (SPD/SPI), and a greedy baseline allocation method (GB) that uses only the VoLL for the allocation of the SLAs. The diversity in criticality β affects the social value achieved by the studied mechanisms. We observe high system inefficiency when buyers demonstrate extreme behavior with regards to the criticality (for large values of β-diversity). Furthermore, SSPA with SLAs of increasing reliability (SPI) performs better than auctioning off SLAs of decreasing reliability (SPD) in terms of the social value. In all settings, the VCG mechanism yields higher social value than all other mechanisms, setting the upper bound due to its socially optimal allocation.

3. CONCLUSION

We proposed a contracting framework through SLAs for electricity trading under uncertain supply and varying demand criticality of the buyers. In view of the attained properties and performance, we believe that using SLAs as we delineated here provides a promising avenue for addressing electricity trading in future smart grids. This work lays the ground for distributed energy trading under uncertainty, serving as a broad basis for future extensions.

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